USAAMRDL TECHNICAL REPORT 73-74

EVALUATION OF VARIOUS SIZES AND CONFIGURATIONS OF FUEL TANKS

By

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December 1973

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

CONTRACT DAAJ02-71-C-0031
FIRESTONE COATED FABRICS COMPANY
DIVISION OF
THE FIRESTONE TIRE & RUBBER COMPANY
MAGNOLIA, ARKANSAS

U. S. ARMY MATERIEL COMMAND

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This report was prepared by Firestone Coated Fabrics Company, Division of Firestone Tire and Rubber Company, under the terms of Contract DAAJ02-71-C-0031. The Eustis Directorate technical monitor for this contract was Mr. H. W. Holland of the Military Operations Technology Division.

The objective of this effort was to conduct the necessary testing to determine the pressures and stresses acting on various fuel tank configurations and to establish the design criteria for maximum tank size and configuration of fuel tanks to allow successful completion of the 65-foot drop test as specified in MIL-T-27422B.

This report has been reviewed by the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory and is published to disseminate information relative to aircraft fuel tank design and test.

Project 1F162203A529
Contract DAAJ02-71-C-0031
USAAMRDL Technical Report 73-74
December 1973

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Final Report

FCFC Report 2097

By

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SUMMARY

Eighteen tanks with a 30-inch x 30-inch base dimension and heights of 48 and 60 inches of qualified crashworthy constructions were impacted from 65 feet. Nine of these failed adjacent to fittings on side panels. All tanks without side fittings passed the impact test regardless of constructions used and with average densities varying from 1.11 to 1.75. Indicated pressures were in the 130-150 psi range for two tanks of Firestone 1550-1 construction and 170-200 psi for a reinforced, heavier revision of this construction.

Strains determined by visual measurement of film records varied from 10 to 21 percent depending on the location on the tank. Those indicated electronically were as high as 60% in the case of the Configuration L tank. The discrepancy between the two methods of strain measurement has not been resolved.

The presence of fittings unquestionably increases the stress in the tank wall in the immediate area adjacent to these fittings and reaches a maximum as the expansion wave of the impacting tank passes the horizontal centerline of the fitting.

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INTRODUCTION

Increasing utilization of crashworthy aircraft fuel tanks produced from fitting and fuel cell constructions acceptable under the requirements of MIL-T-27422B brought to light the inadequacies of these constructions when applied to the diverse configurations, sizes, and fitting placements typical of actual aircraft fuel tanks. In an attempt to provide criteria for the designing of large-volume crashworthy fuel tanks, the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory awarded Contract DAAJ02-71-C-0031 for the fabrication and testing of tanks of different heights (48 and 60 inches) and with varying quantities of side fittings (0, 1, or 2). The data obtained from the impact tests were then analyzed for the following:

1. Effects of capacity or volume on pressures.
2. Effects of capacity or volume on strain.
3. Effects of single and double fittings on the strain data obtained from tanks with no fittings.
4. Hydraulic ram as affected by capacity and tank orientation.

Although not completely successful due in large part to the formidable instrumentation problems involved with falling tanks, considerable data was obtained and is presented.

FUEL TANK CONFIGURATIONS

Eighteen tanks were built from Firestone Construction 1550-1 or a reinforced version, 1550-1E. These tanks were produced from constructions and fittings qualified to MIL-T-27422B. The drop log, Table I, includes pertinent data for all tanks tested.

In the first group of tanks in Table I, it can be noted that those tanks which contained no side fitting successfully passed the impact test, while all tanks with one or more side fittings failed. All ruptures were initiated by tensile failure of tank and/or fitting plies at the horizontal centerline of the fitting followed by tearing of tank plies upward and downward along the bias cords. Due to these failures, the average areal density requirement was established at 1.80 $\pm$ .15 for the second group shown on the drop log which permitted the addition of reinforcing plies to both the panel and fitting constructions. All tanks of the second group passed the impact tests.

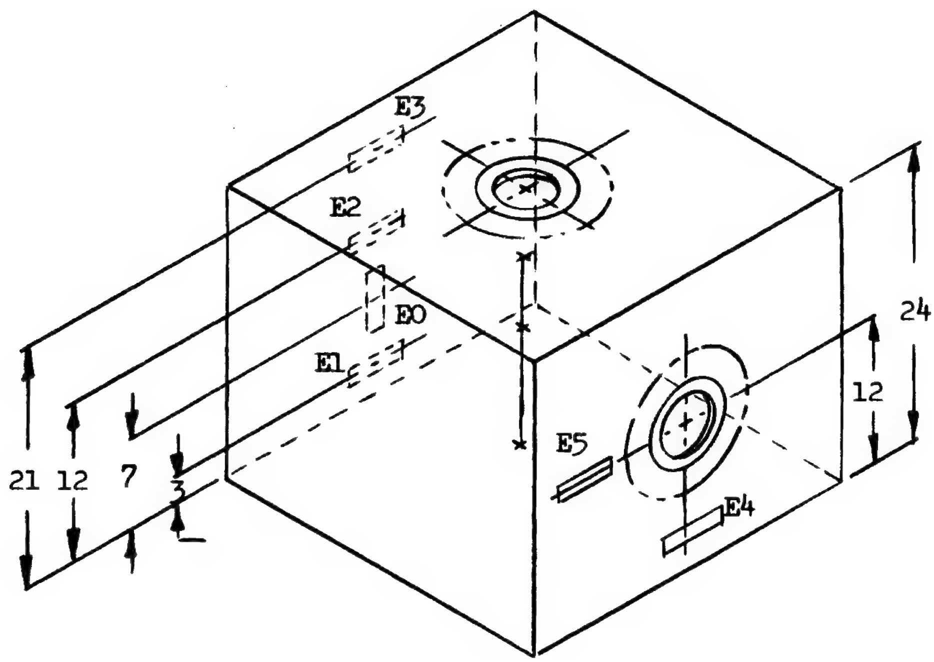
Sketches of the configurations used in this program are given in Figures 1 through 9.

TABLE I. FUEL TANK DROP TEST SEQUENCE

TEST NO.	SK NO.	CONFIGURATION	TANK SERIAL NO.	SIDE FITTINGS NO.	TANK HEIGHT (in)	TANK WEIGHT (lb)	AVG. DENSITY (lb/sq ft)	IMPACT FACE	CONTAINED WATER (lb)	% FILL	RESULT
	CONSTRUCTION 1550-1, REGULAR FITTING										
1	2286	A	56882	1	24	41.5	1.33	Top**	684	100	Passed
2	2286-2	A/A-1	56885/56886	2	48	41.0/39.5	1.31/1.27	Bottom	1344	97	Failed
3	2287	B	57122	1	48	59.0	1.15	Bottom	1448	100	Failed
4	2287	B	57121	1	48	54.5	1.11	Bottom	1419	100	Failed
5	2287-1	B-1	57123	1	48	59.0	1.15	Bottom	1445	100	Failed
6	2288	C	57129	1	60	70.0	1.14	Side	1860	100	Failed
9	2289	D	57124	2	48	60.5	1.18	Bottom	1448	100	Failed
10	2289	D	57125	2	48	61.0	1.19	Bottom	1440	97	Failed
11	2288-1	C-1	57133	1	60	70.0	1.14	Side	1910	97	Failed
12	2290	E	57128	0	48	57.0	1.11	Bottom	1441	100	Passed
13	2290	E	57127	0	48	58.5	1.14	Bottom	1460	100	Passed
14	2291	F	57131	0	60	67.8	1.10	Side	1854	100	Failed
	REINFORCED 1550-1 CONSTRUCTION, REINFORCED FITTING										
7	2288	L	E-1210	1	60	110.0	1.79	Bottom	1876	100	Passed
8	2290	H	E-1208	0	48	89.5	1.75	Bottom	1496	100	Passed
15	2291	K	E-1209	0	60	106.8	1.74	Bottom	1868	100	Passed
16	2287	I	E-1205	1	48	83.5	1.59	Bottom	1456	100	Passed
17	2289	J	E-1211	2	48	96.0	1.87	Bottom	1494	100	Passed
18	2286-2	G/G-1	E-1212/E-1213	2	48	60.8/63.0	1.95/2.02	Bottom	1384	100	Passed

* All tanks had fitting on nominal "top" of tank.

** Initial test cube for procedure check-out allowed to free fall, subsequent tanks dropped on guided platform.

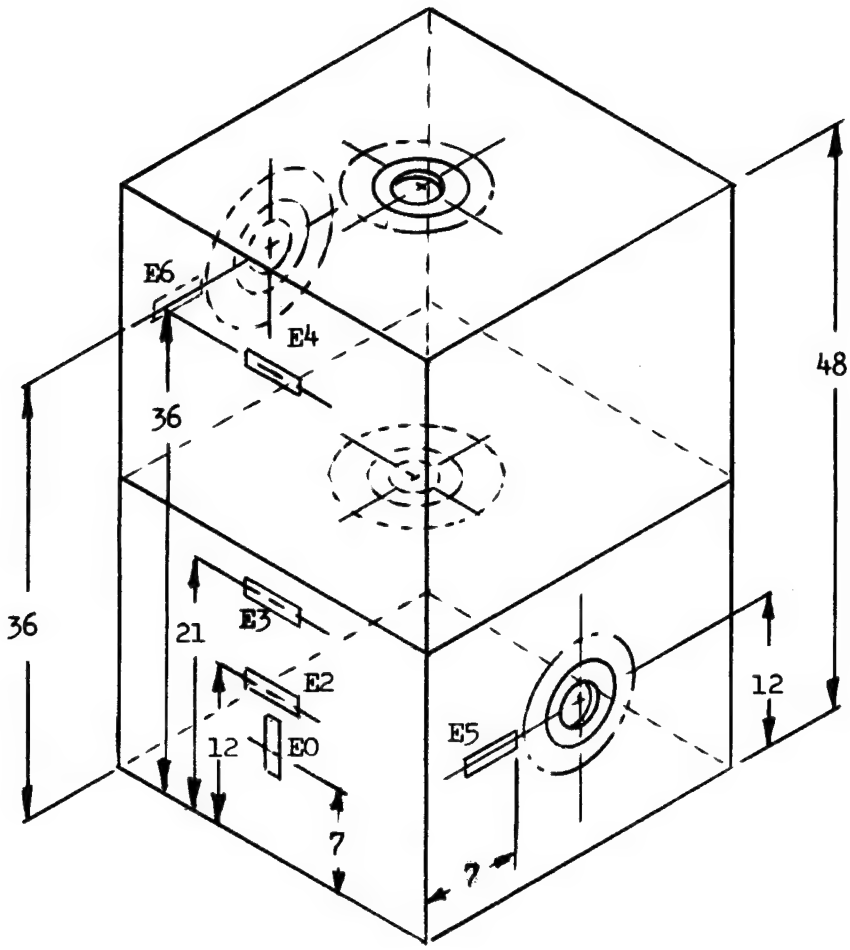


INSTRUMENTATION

Pressure: Statham Transducer mounted in top fitting plate. Kistler Transducers mounted 3 inches, 12 inches and 21 inches from bottom on vertical centerline.

Strain: E0: Vertically oriented strain gage. E1 through E5: Horizontally-oriented strain gages.

Figure 1. Configuration A.

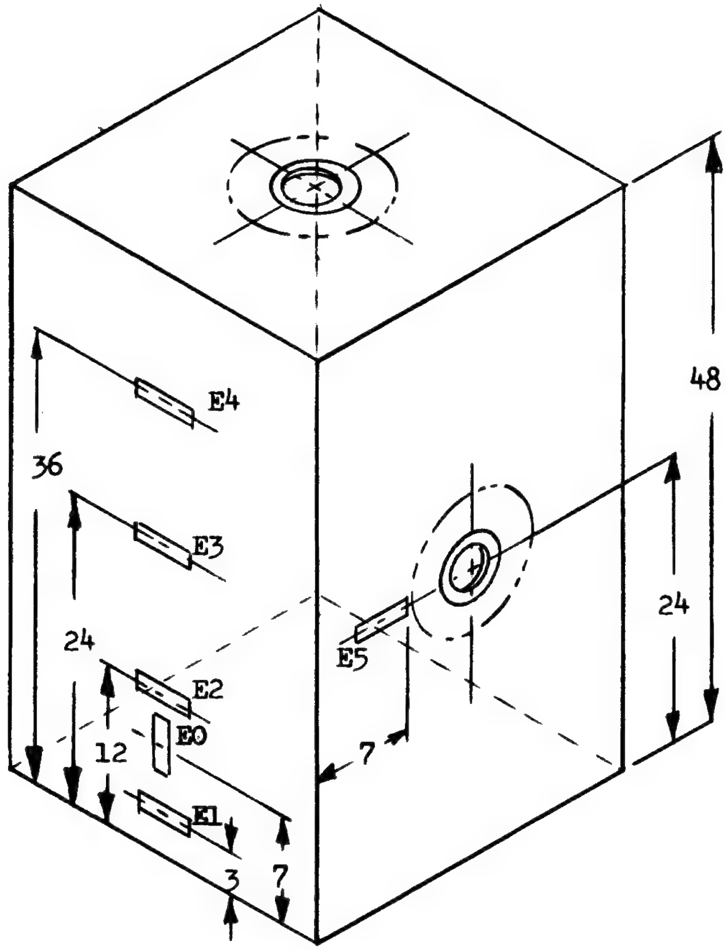


INSTRUMENTATION

Pressure: Statham Transducer mounted in top fitting plate. Kistler Transducers mounted 3 inches, 12 inches, 21 inches and 36 inches from bottom on vertical centerline.

Strain: E0: Vertically oriented strain gage.
E1 through E5: Horizontally-oriented strain gages.

Figure 2. Configurations A/A1 and G/G1.

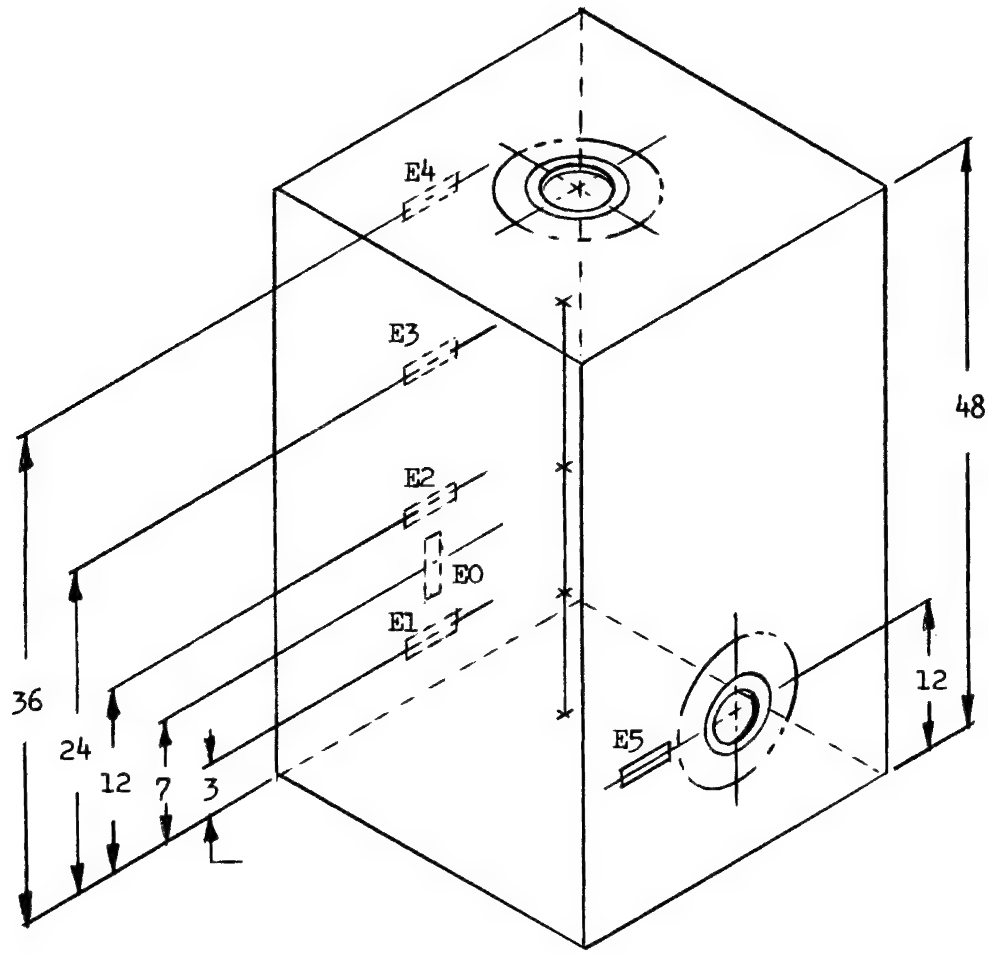


INSTRUMENTATION

Pressure: **Statham Transducer mounted in top fitting plate. Kistler Transducers mounted 3 inches, 12 inches, 24 inches and 36 inches from bottom on vertical centerline.**

Strain: **E0: Vertically oriented strain gage.**
E1 through E5: Horizontally-oriented strain gages.

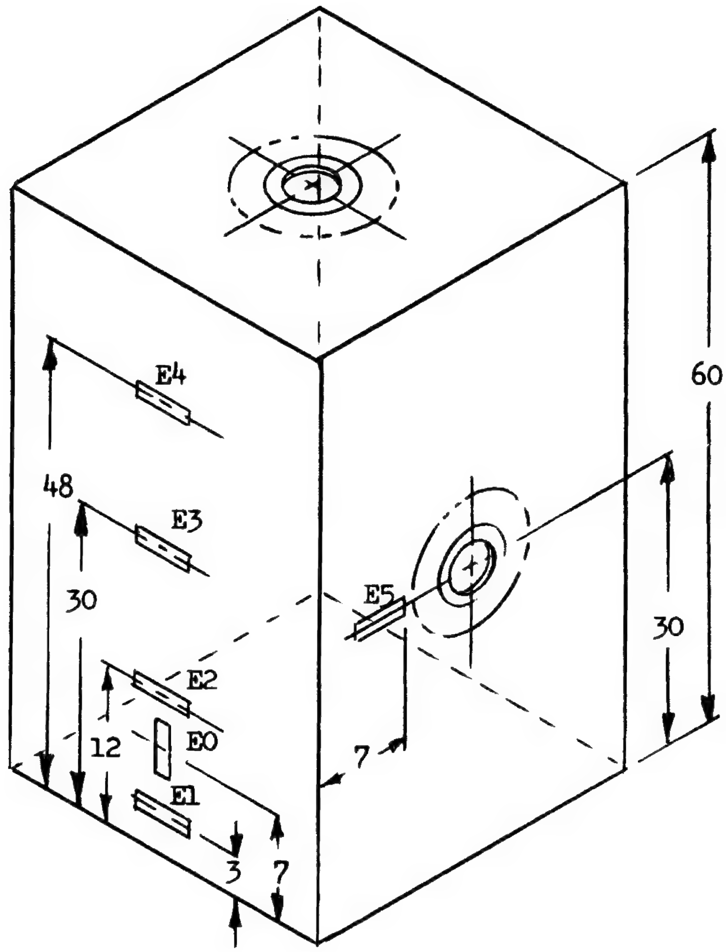
Figure 3. Configurations B and I.



INSTRUMENTATION

Pressure:	Statham Transducer mounted in top fitting plate. Kistler Transducers mounted 3 inches, 12 inches, 24 inches and 36 inches from bottom on vertical centerline.
Strain:	E0: Vertically oriented strain gage. E1 through E5: Horizontally-oriented strain gages.

Figure 4. Configuration B-1.

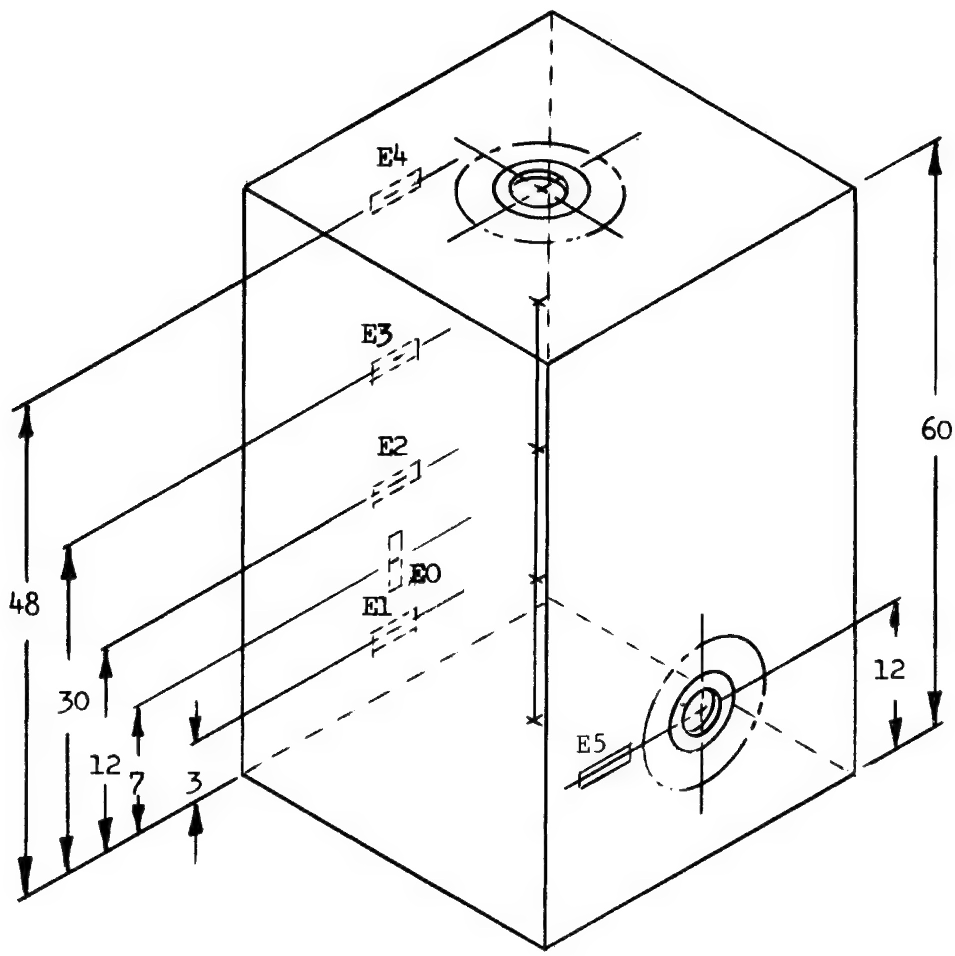


INSTRUMENTATION

Pressure: Statham Transducer mounted in top fitting plate. Kistler Transducers mounted 3 inches, 12 inches, 30 inches and 48 inches from bottom on vertical centerline.

Strain: E0: Vertically oriented strain gage. E1 through E5: Horizontally-oriented strain gages.

Figure 5. Configurations C and L.

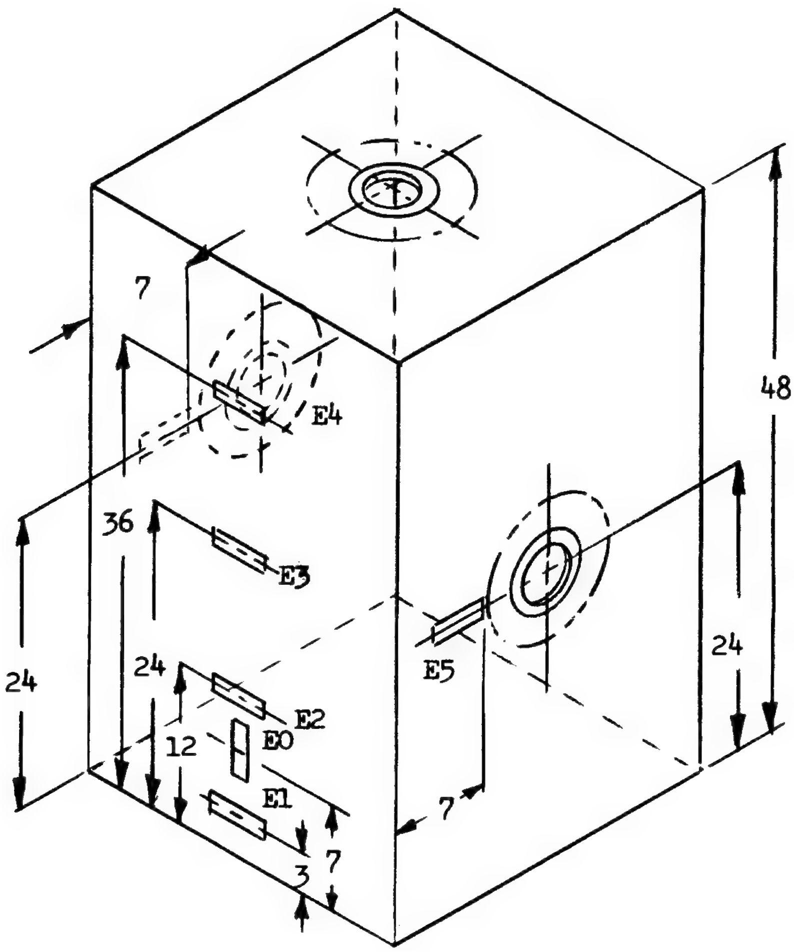


INSTRUMENTATION

Pressure: Statham Transducer mounted in top fitting plate. Kistler Transducers mounted 3 inches, 12 inches, 30 inches and 48 inches from bottom on vertical centerline.

Strain: E0: Vertically oriented strain gage. E1 through E5: Horizontally-oriented strain gages.

Figure 6. Configuration C-1.

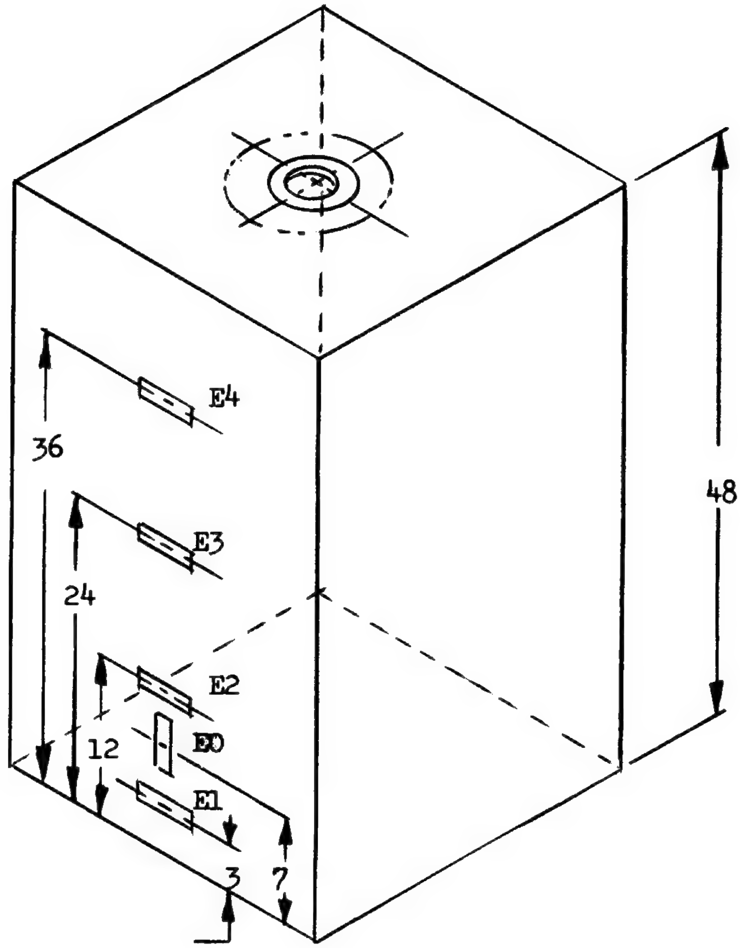


INSTRUMENTATION

Pressure: Statham Transducer mounted in top fitting plate. Kistler Transducers mounted 3 inches, 12 inches, 24 inches and 36 inches from bottom on vertical centerline.

Strain: E0: Vertically oriented strain gage. E1 through E5: Horizontally-oriented strain gages.

Figure 7. Configurations D and J.

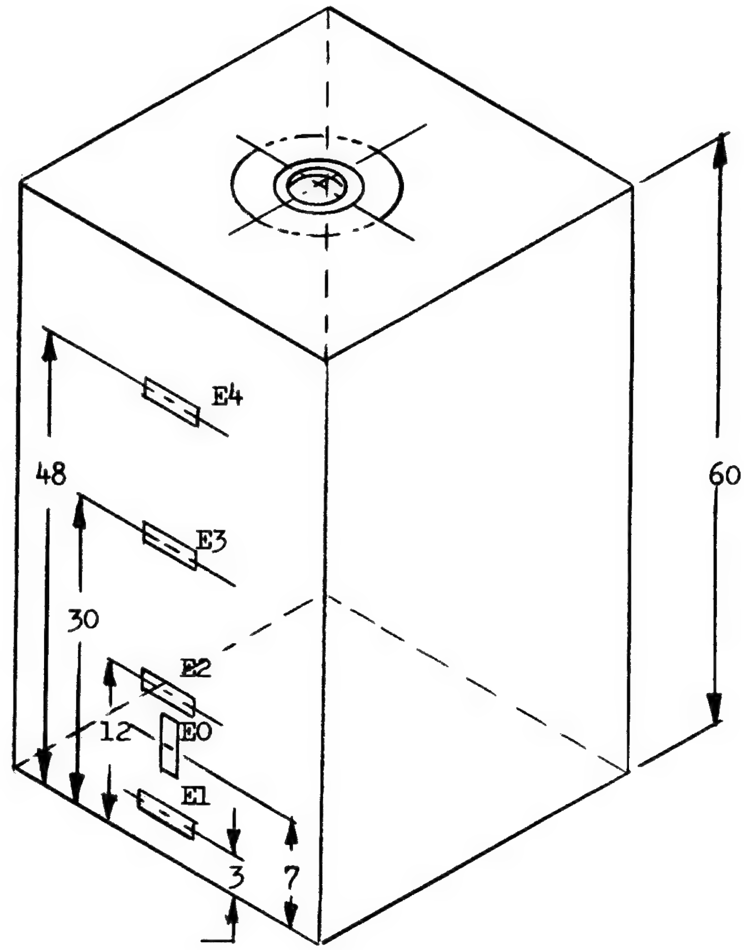


INSTRUMENTATION

Pressure: Statham Transducer mounted in top fitting plate. Kistler Transducers mounted 3 inches, 12 inches, 24 inches, and 36 inches from bottom on vertical centerline.

Strain: E0: Vertically oriented strain gage. E1 through E4: Horizontally-oriented strain gages.

Figure 8. Configurations E and H.



<u>**INSTRUMENTATION**</u>

Pressure:	**Statham Transducer mounted in top fitting plate. Kistler Transducers mounted 3 inches, 12 inches, 30 inches and 48 inches from bottom on vertical centerline.**
Strain:	**E0: Vertically oriented strain gage. E1 through E4: Horizontally-oriented strain gages.**

Figure 9. Configurations F and K.

FUEL TANK DROP TESTS

Initially, it was intended that tanks would be installed in the fill fixture shown in Figure 10 for the purpose of instrumentation, filling and dropping. While it was the intent to use this fixture with a trap door on the bottom to permit free drops of the tanks, this approach was proven to be impractical on the first drop. The tank rotated approximately 150° and impacted on the top face at a point between the top fitting and the side wall containing the side fitting. Consequently, direct impact of the fittings on the concrete occurred, causing side cover plate bending and the loss of an insignificant amount of water. Destruction of the top cover plate transducer, shown in Figure 11, on another tank was total, and many of the coaxial cables, caught between the top fitting and the lower base, were severed and required replacement. The impact position of this tank is shown in Figure 12.

Subsequent to this drop, the fill fixture was used only for strain gage location and to maintain the tank in a simulated "aircraft" configuration while being filled to capacity and evacuated. A number of drops were then performed on a guided platform of the type shown aloft in Figure 13. This platform design caused the rebounding tank to strike the crosspiece between the vertical uprights and threatened damage to the top transducer, cable entry point and cables. The platform release was then redesigned to the configuration shown in Figure 14, wherein the hinged crossarm remained aloft and offered no threat to the instrumentation. Two tanks, however, did fall on the projecting ends of the vertical uprights after rebound; but neither incident resulted in any serious damage to the tanks, and this system was used for the remainder of the drops. All drops were made from 65 feet.

As indicated by Table II, Configurations A/A-1 and D were dropped with 3% ullage to determine if this would reduce the incidence of failure. Also, Configurations C, C-1 and F were dropped in a horizontal attitude (on their side) and with 0 and 3% ullage to determine the effect of these variables. All resulted in failures with apparently the same pressures being developed as with the vertical drop attitude. Therefore, it appears that with a given construction, total volume and/or perimeter may be at least as important as tank height.

Figure 10. Fixture for Fill and Instrumentation Location.

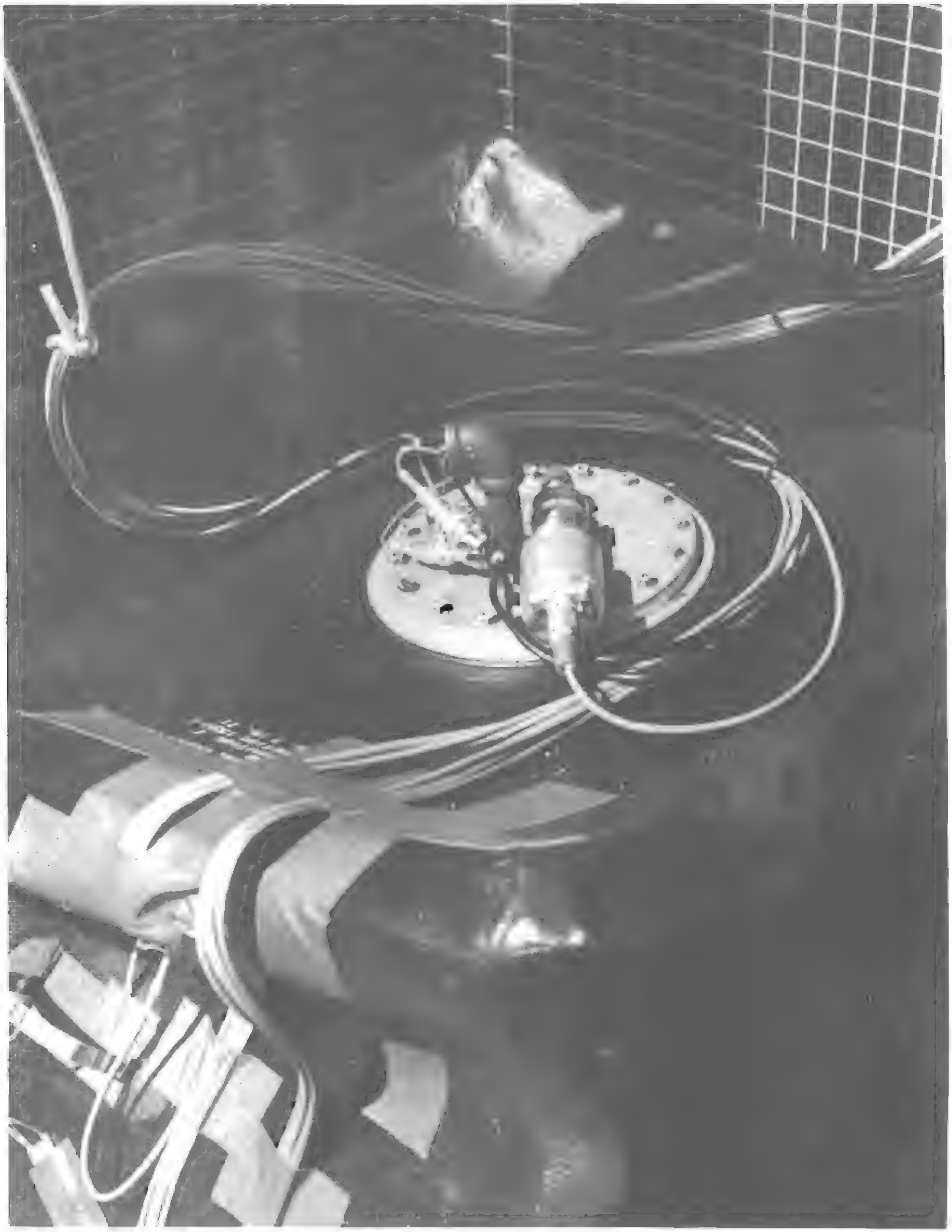


Figure 11. Entry Point of Pressure Leads and Statham Transducer.

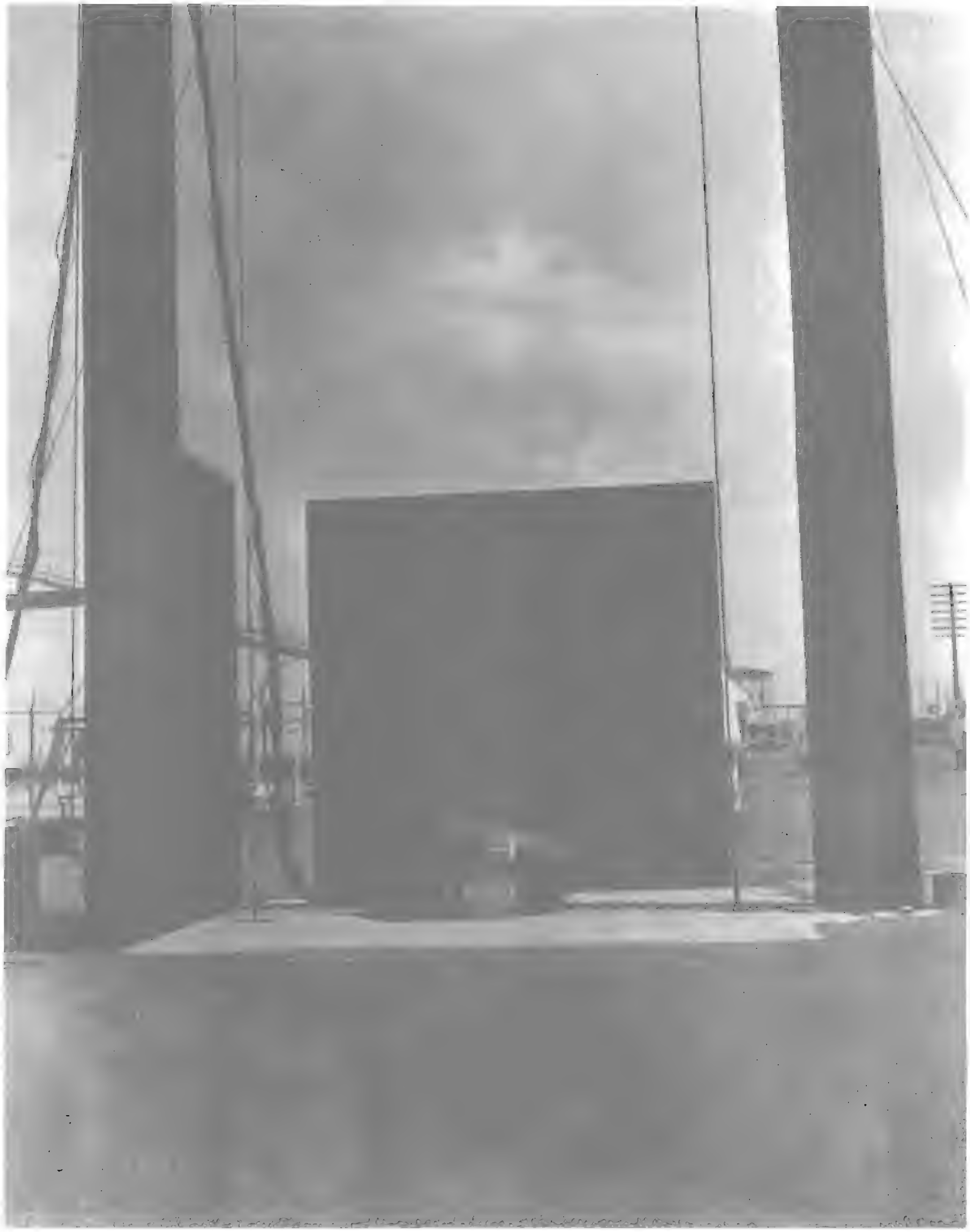


Figure 12. Impact of Procedure Check-Out Tank

Figure 13. Tower With Test Tank Aloft.

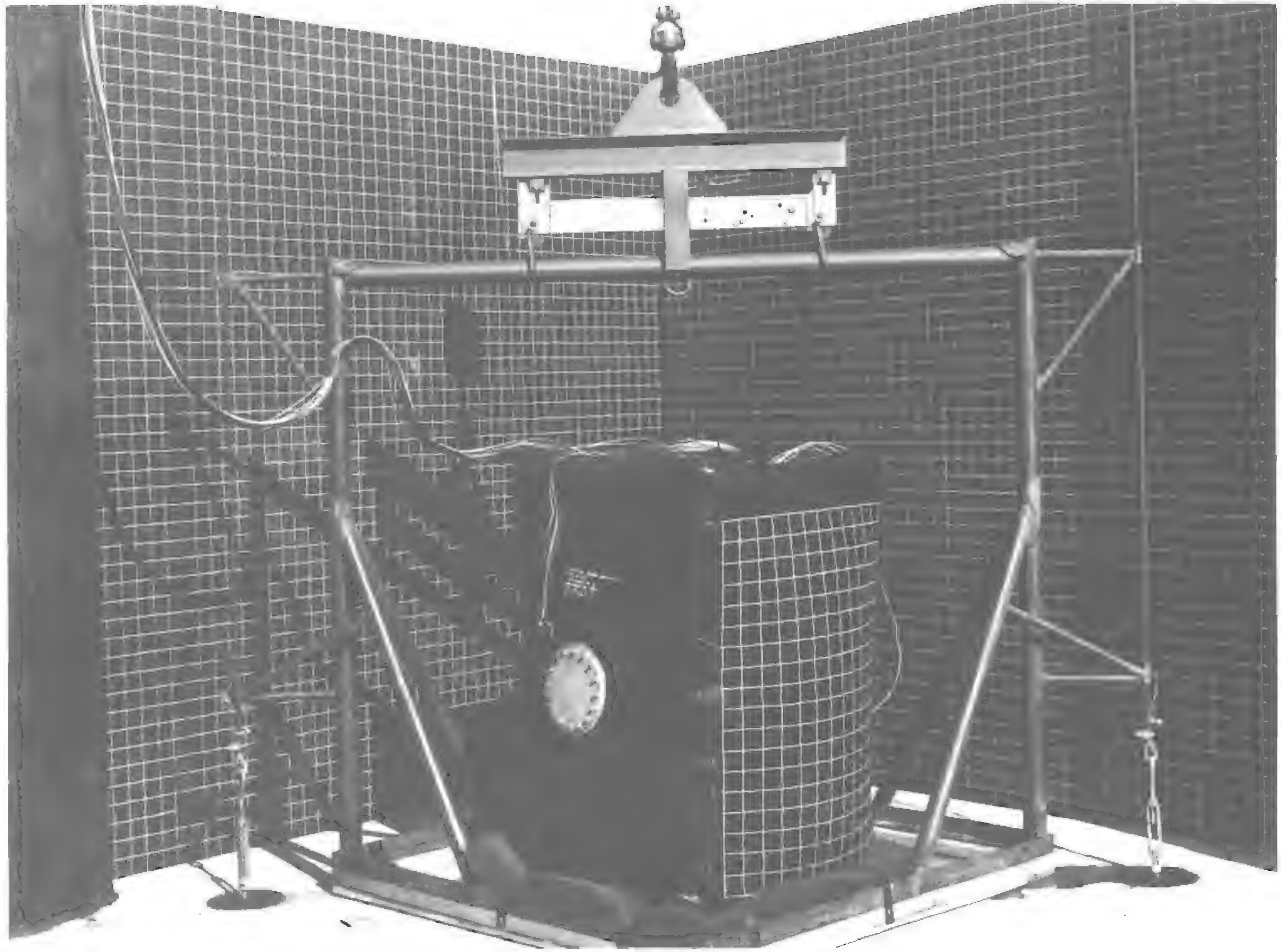


Figure 14. Modified Release Mechanism to Eliminate Permanent Crossarm.

DATA RECORDING

I. ELECTRONIC DATA GATHERING AND RECORDING

A. Pressure Measurement

The vertical pressure distribution was measured in each case by four Kistler 603A piezoelectric transducers suspended along the vertical axis of the fuel tank. This was accomplished by attaching these with the sensing head facing the tank impact face, to an elastic cord which was slightly pretensioned and anchored to the center of the impact face and to the top fitting cover plate by means of small D-rings. The output from each transducer was fed into a Kistler Model 503 charge amplifier for conditioning. The charge amplifier's output was then fed into a CEC 1-114B galvanometer driver amplifier, then to a CEC 7-362 galvanometer in the 36-channel CEC 5-119 recording oscillograph. The limiting item for frequency response would have been the galvanometer, which has a range of 0-5000 cycles per second.

A fifth transducer, a Statham strain type, was attached to the top fitting cover plate to sense pressure at that point. Recording was accomplished with a CEC 7-323 galvanometer.

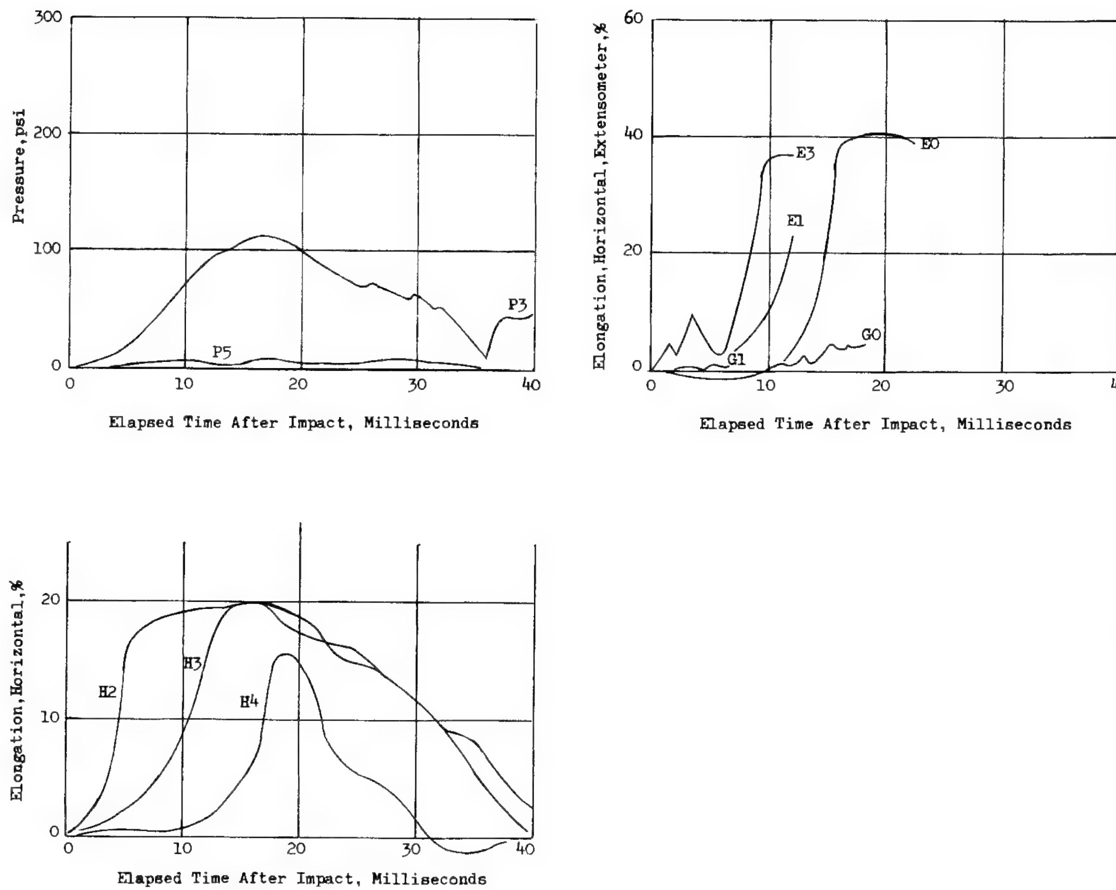
Pressure Measurement Difficulties

Problems occurred in pressure measurement primarily in four areas:

1. The coaxial cables were extremely susceptible to damage. As can be seen in Figure 13, the cables extend from the instrumentation package to the drop platform and are attached to the tower at approximately the midpoint. This, the best of several ways tried, still resulted in a loop which was subject to sway in breezes and snagging on the falling platform.

2. As explained earlier, the internal pressure transducers were suspended on an elastic cord on the vertical axis of the tank. On occasional impacts, the cord became disengaged from the top fitting cover and the combined retraction of the cord and deceleration tensioned the coaxial cable connected to the pressure transducers, although slack had been allowed for reasonable movement. This often resulted in the cables' being pulled through the top fitting and could explain some of the lost signals.

3. Due to cable movement and changing capacitance, the "zero" reference point of the Kistler transducer readout frequently shifted during and subsequent to impact. The pressure data offered in this report in Figures 15 through 22 has been smoothed in an attempt to take into account the reference shift as well as to remove extraneous noise.



Test No. 13
Configuration E
SK2290 S/N 57127
Construction 1550-1
Tank Height - 48 inches
Drop Height - 65 feet

Instrumentation Location:

Pressure:

Transducer	Distance From Impact Face
P1	3"
P2	12"
P3	24"
P4	36"
P5	48"

Elongation:

Extensometer (Clip)

E0	Vert.	7"
E1	Horiz.	3"
E2	Horiz.	12"
E3	Horiz.	24"
E4	Horiz.	36"

Strain Gage

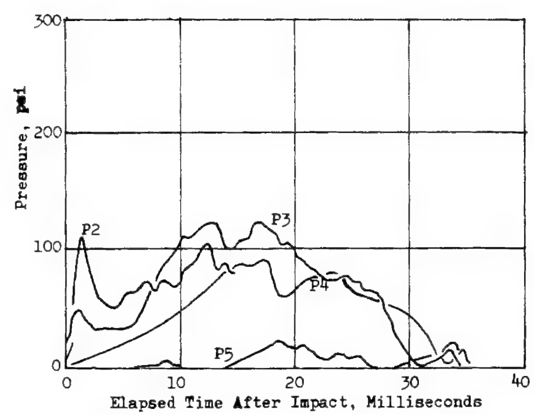
G0	Vert.	7"
G1	Horiz.	3"
G2	Horiz.	12"
G3	Horiz.	24"
G4	Horiz.	36"

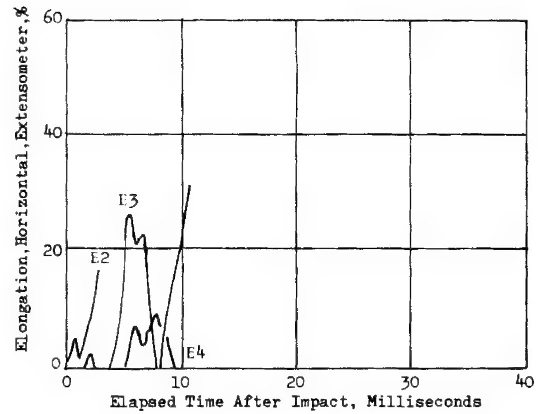
Visual Strain Measurements:

Horizontal:

H2	12"
H3	24"
H4	36"

Figure 15. Pressure and Elongation Data for Configuration E.





Test No. 12
Configuration E
SK2290 S/N 57128
Tank Height - 48 inches
Drop Height - 65 feet

<u>Instrumentation Location:</u>

Pressure:

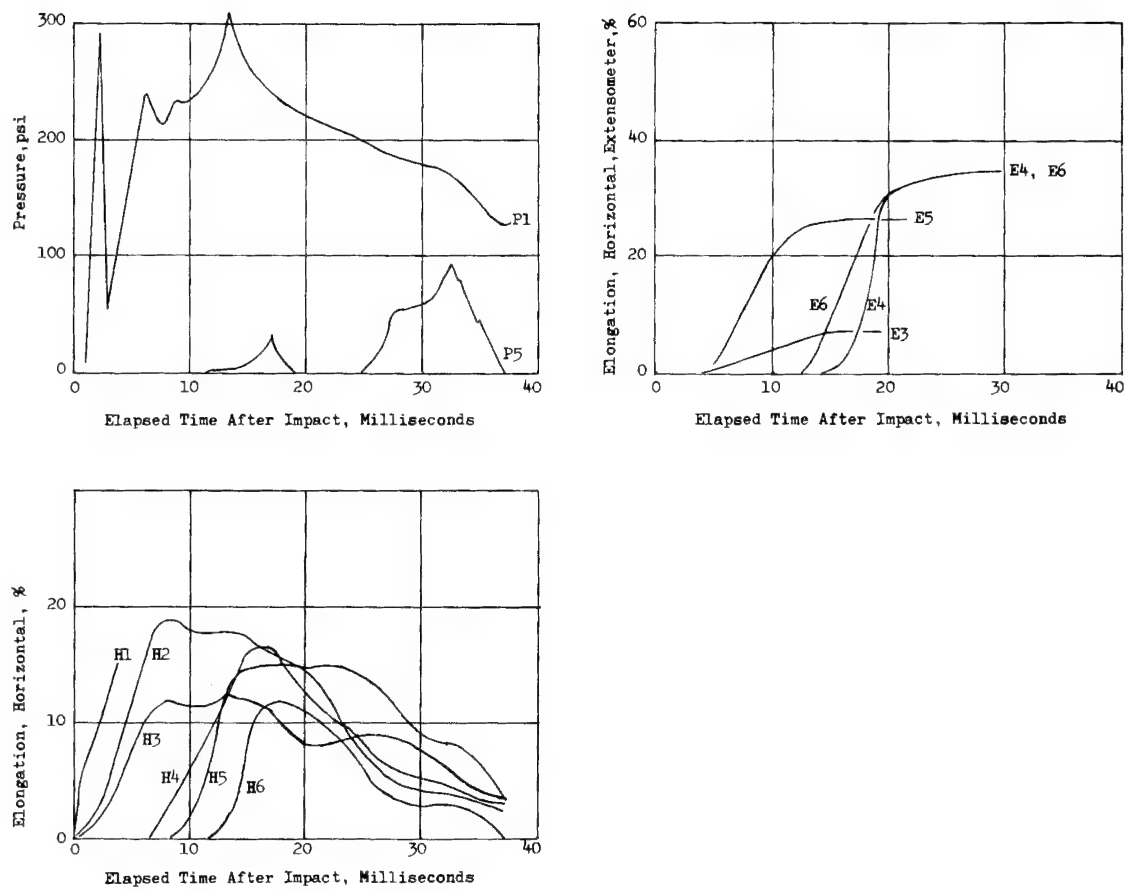
Transducer	Distance From Impact Face
P1	3"
P2	12"
P3	24"
P4	36"
P5	48"

Elongation:

Extensometer (Clip)		
E0	Vert.	7"
E1	Horiz.	3"
E2	Horiz.	12"
E3	Horiz.	24"
E4	Horiz.	36"

No visual strain determination made.

Figure 16. Pressure and Elongation Data for Configuration E.



Test No. 18
Configuration G/G-1
SK2286-2 S/N E1212/E1213
Construction 1550-1E
Tank Height - 48 inches
(Hydraulically coupled)
Drop Height - 65 feet

Instrumentation Location:

Pressure:

Transducer	Distance From Impact Face
P1	3"
P2	12"
P3	21"
P4	36"
P5	48"

Elongation:
Extensometer

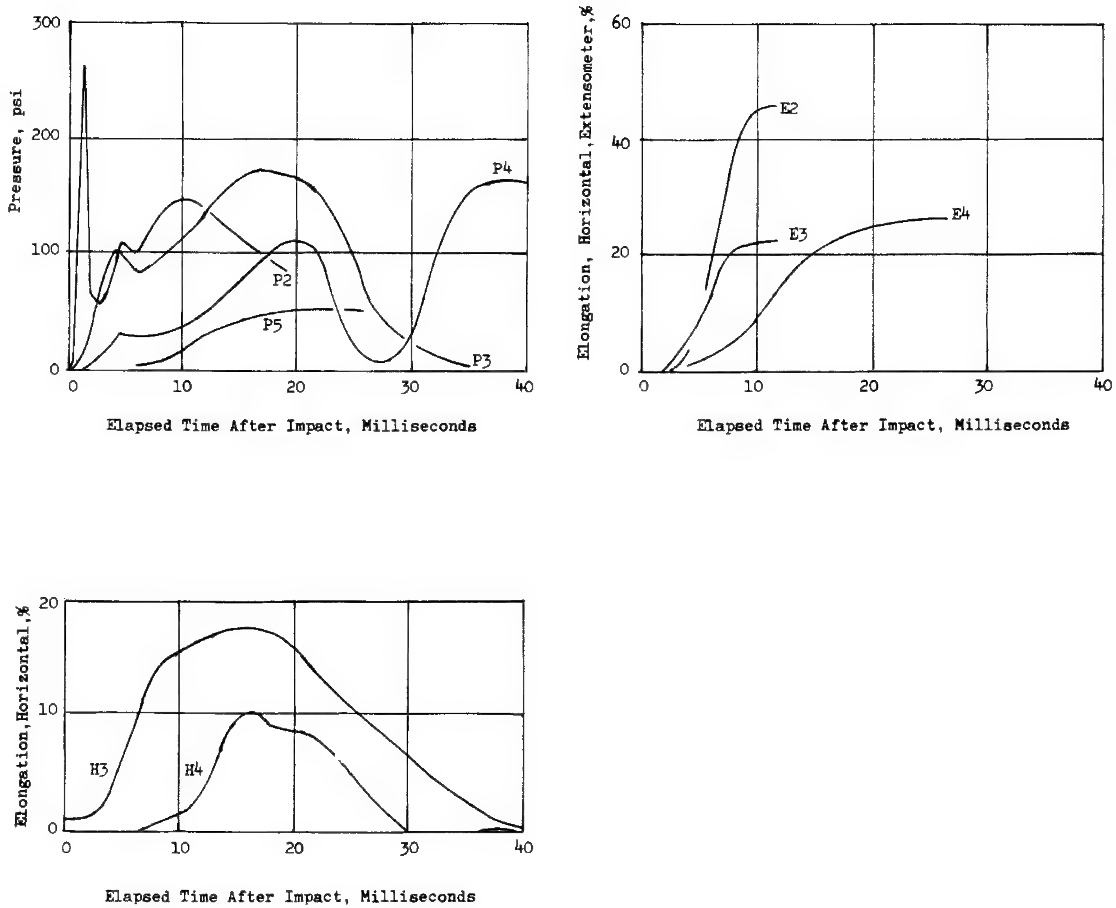
E0	Vert.	7"
E2	Horiz.	12"
E3	Horiz.	21"
E4	Horiz.	36"
E5	Horiz.	12"
	(Lower ftg. centerline)	
E6	Horiz.	36"
	(Upper ftg. centerline)	

Visual Strain Measurements:

Horizontal:

H1	7"
H2	12"
H3	17"
H4	31"
H5	36"
H6	41"

Figure 17. Pressure and Elongation Data for Configuration G/G-1.



Test No. 8
Configuration H
SK2290 S/N E1208
Construction 1550-1E
Tank Height - 48 inches
Drop Height - 65 feet

<u>Instrumentation Location:</u>

Pressure:

Transducer	Distance From Impact Face
P1	3"
P2	12"
P3	24"
P4	36"
P5	48"

Elongation:

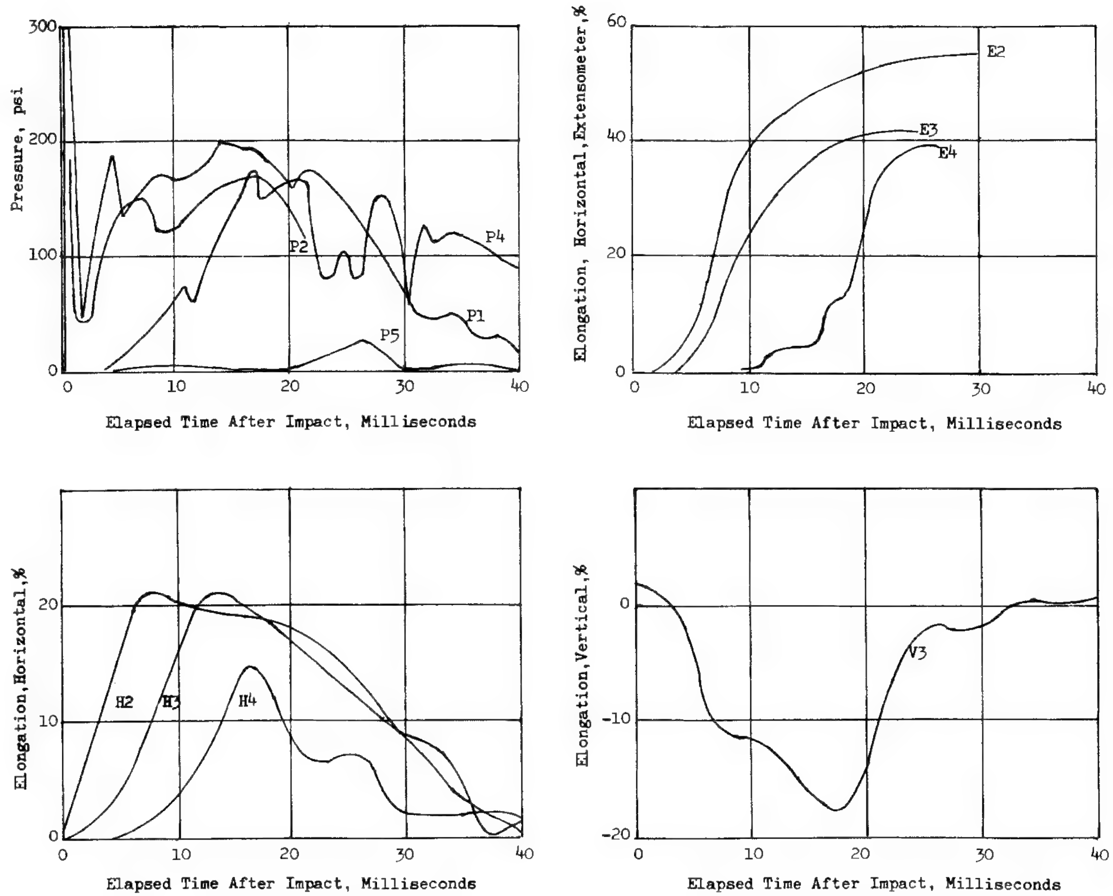
Extensometer		
E0	Vert.	7"
E2	Horiz.	12"
E3	Horiz.	24"
E4	Horiz.	36"

<u>Visual Strain Measurements:</u>

Horizontal:

H2(obscured by dust)	
H3	24"
H4	36"

Figure 18. Pressure and Elongation Data for Configuration H.



Test No. 16
Configuration I
SK2287 S/N E1205
Construction 1550-1E
Tank Height - 48 inches
Drop Height - 65 feet

Instrumentation Location:

Pressure:

Transducer	Distance From Impact Face
P1	3"
P2	12"
P3	24"
P4	36"
P5	48"

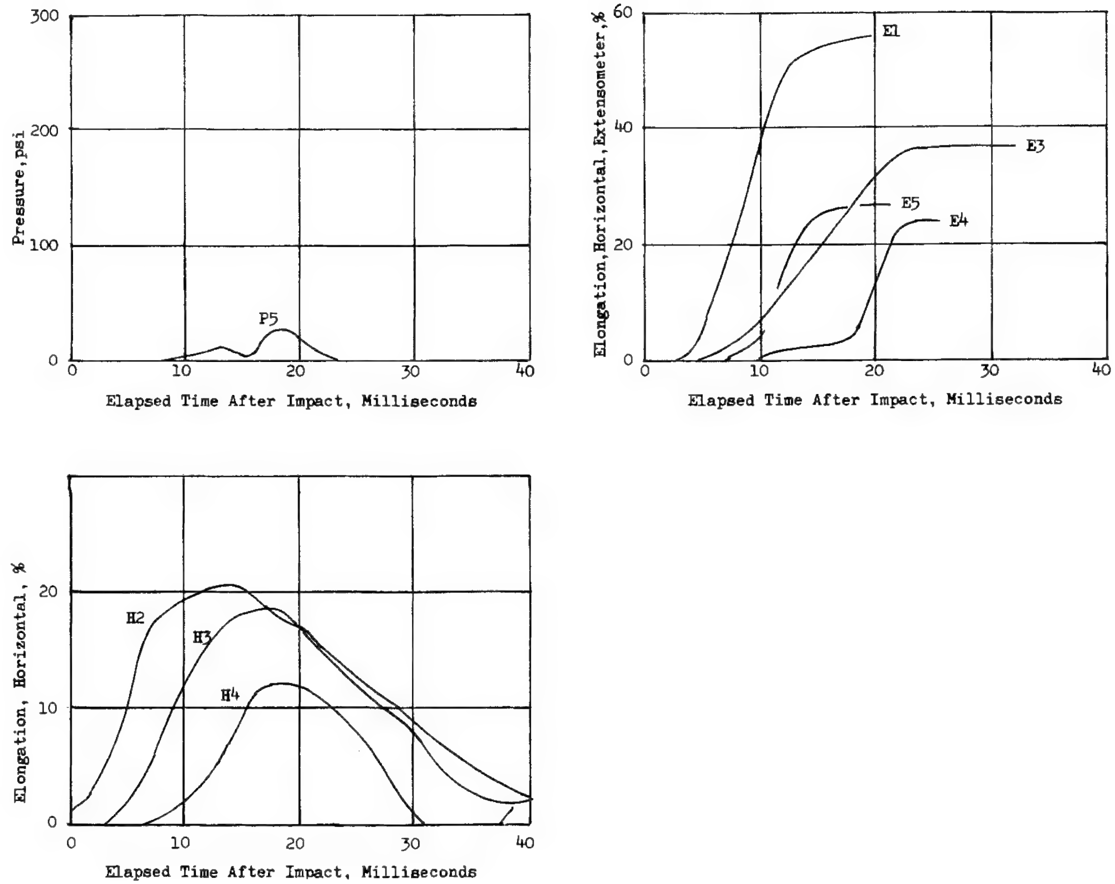
Elongation:

Extensometer		
E0	Vert.	7"
E2	Horiz.	12"
E3	Horiz.	24"
E4	Horiz.	36"

Visual Strain Measurements:

Horizontal:	
H2	12"
H3	24"
H4	36"
Vertical:	
V3	22-28"

Figure 19. Pressure and Elongation Data for Configuration I.



Test No. 17
Configuration J
SK2289 S/N E1211
Construction 1550-1E
Tank Height - 48 inches
Drop Height - 65 feet

<u>Instrumentation Location:</u>

Pressure:

Transducer	Distance From Impact Face
P1	3"
P2	12"
P3	24"
P4	36"
P5	48"

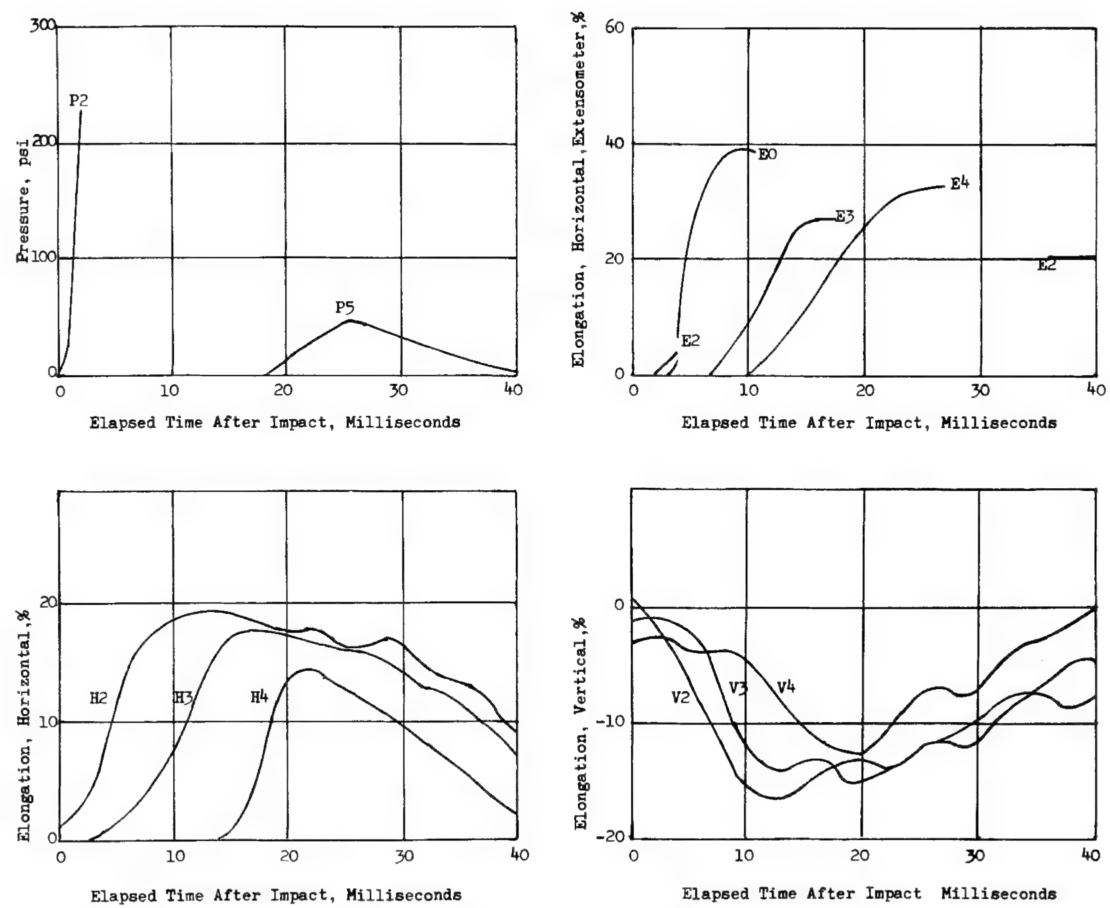
Elongation:

Extensometer		
E0	Vert.	7"
E2	Horiz.	12"
E3	Horiz.	24"
E4	Horiz.	36"
E5	Horiz.	24"

<u>Visual Strain Measurements:</u>

Horizontal:	
H2	12"
H3	24"
H4	36"

Figure 20. Pressure and Elongation Data for Configuration J.



Test No. 15
Configuration K
SK2291 S/N E-1209
Construction 1550-1E
Tank Height - 60 inches
Drop Height - 65 feet

Instrumentation Location:

Pressure:

Transducer	Distance From Impact Face
P1	3"
P2	15"
P3	30"
P4	45"
P5	60"

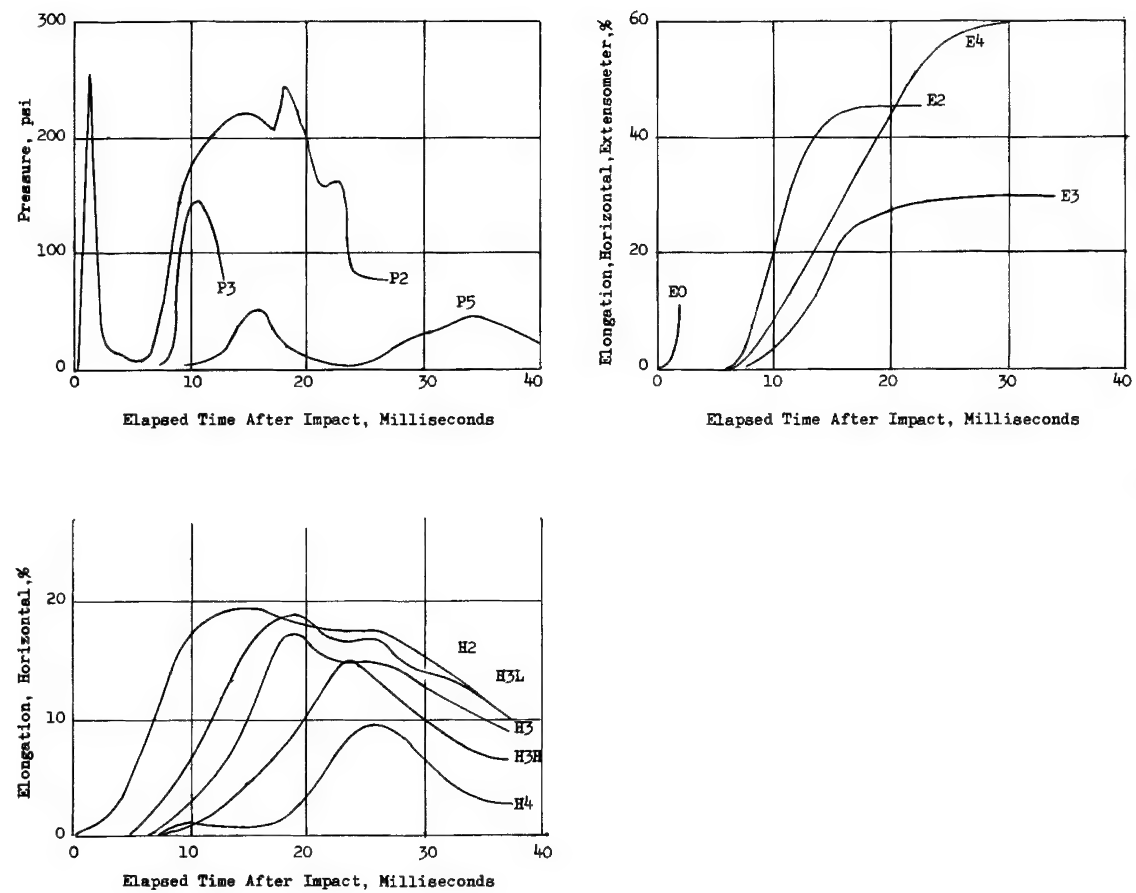
Elongation:

Extensometer		
E0	Vert.	7"
E2	Horiz.	15"
E3	Horiz.	30"
E4	Horiz.	45"

Visual Strain Measurements:

Horizontal:	Distance From Impact Face
H2	15"
H3	30"
H4	45"
Vertical:	
V2	14-20"
V3	28-34"
V4	40-46"

Figure 21. Pressure and Elongation Data for Configuration K.



Test No. 7
Configuration L
SK2288 S/N E1210
Construction 1550-1E
Tank Height - 60 inches
Drop Height - 65 feet

<u>Instrumentation Location:</u>

Pressure:

Transducer	Distance From Impact Face
P1	3"
P2	15"
P3	30"
P4	45"
P5	60"

Elongation:

Extensometer		
E0	Vert.	7"
E2	Horiz.	12"
E3	Horiz.	30"
E4	Horiz.	48"

<u>Visual Strain Measurements:</u>

Horizontal:	Distance From Impact Face
H2	15"
H3L	24"
H3	30"
H3H	36"
H4	45"

Figure 22. Pressure and Elongation Data for Configuration L.

4. In many cases, the rapid onset of pressures and the presence of signal interference caused such rapid fluctuations of the light-beam oscillograph that the traces became so faint that they were essentially invisible.

B. Strain Measurement

It was initially anticipated that elongations up to 20% would be measured by BLH PA3 post-yield strain gages. It was found, however, that these gages ceased to function in most cases at approximately 5% apparently due to the excessive strain rate, which often approached 3000%/second. Their use was therefore discontinued after the fourth drop.

Clip-type extensometers, depicted in Figure 23, with full bridge foil strain gages attached to their faces, were utilized for four of the initial impact tests since they possessed capability of measuring up to 50% strain. The output from these, as well as that from the BLH PA3 gages, was fed into CEC 3KC carrier amplifiers and then to 7-323 galvanometers in the light-beam recording oscillograph. The limiting item for frequency response was the 3KC carrier amplifiers, which had a flat response from 0 to 600 cycles per second.

Separate special mounting pads at each end of the clip extensometers permitted individual mounting of each end of the extensometers and freedom of movement of the tank wall. Difficulties were encountered, however, in two areas with these extensometers. First, the inertia of the bowed metal projecting outward from the tank wall produced high bending moments at the mounting pad which frequently tore the extensometer from the pads during the contortions of the tank upon impact. Some of these were found as far as 50 feet from the tank. Attempts made to redesign and reinforce the mountings improved the condition, but never entirely corrected it.

Second, extensometers located near the tank impact face were trapped between the tank and the platform as the tank expanded upon impact. This not only obviously affected the measurement but also presented the possibility of tank damage to the point of failure since the sharp edge of the metal clip was frequently against the tank after being distorted. (See Figure 24.) In fact, one tank, Serial No. 57128, sustained a 2-inch cut through the inner liner, but did not tear. Leakage of water was minimal, and the tank successfully sealed as long as the wound was not misaligned. Photographs of the damaged tank as it came to rest are given in Figures 25 and 26. Because of the above difficulties, testing was suspended at that point until a more satisfactory strain gage could be devised.

A slide wire extensometer was then designed to replace the other gages. Although this extensometer would not permit continuous readout since it was limited to measuring increasing elongation,

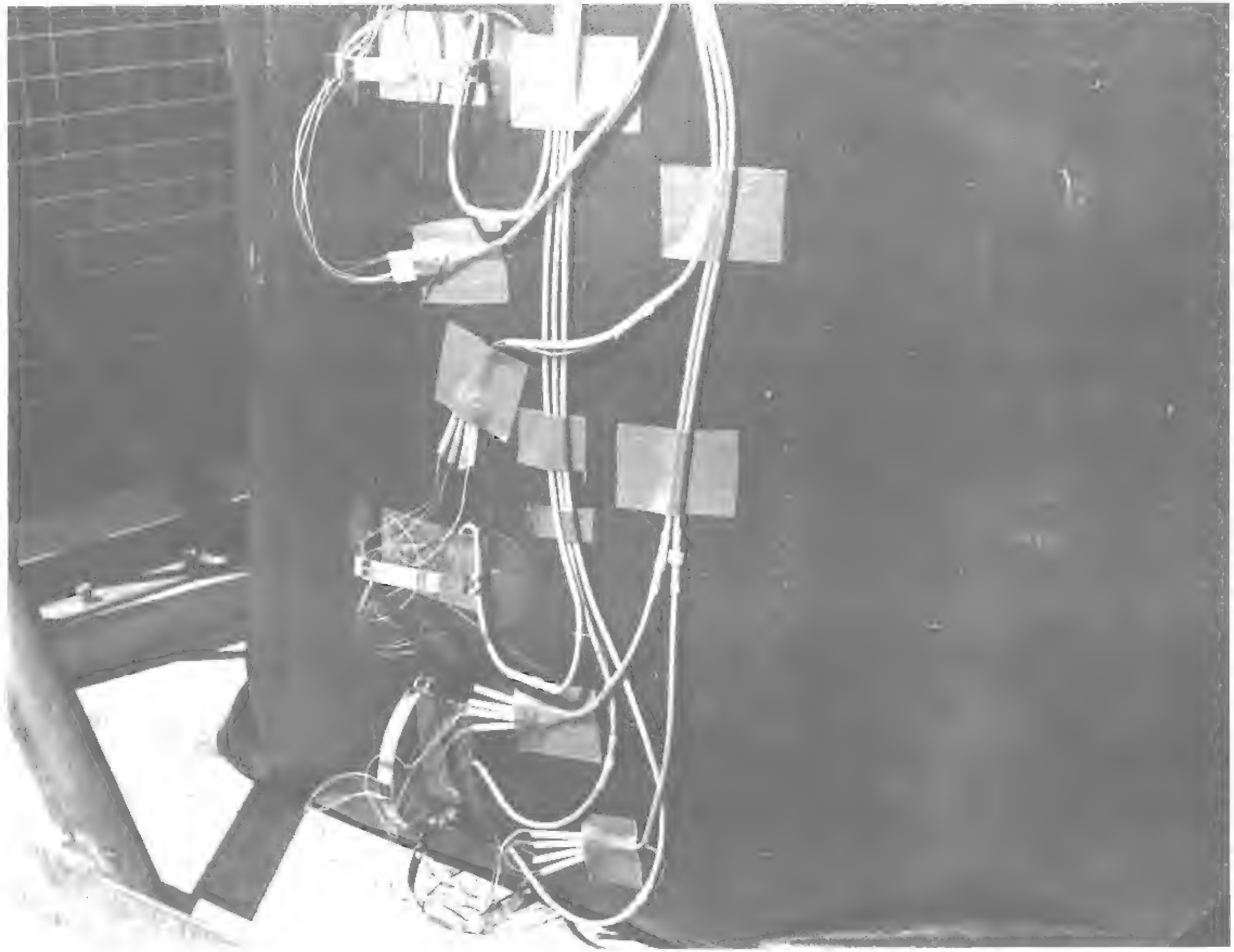


Figure 23. Full-Bridge Clip Extensometers

Figure 24. Clip Damage During Impact.

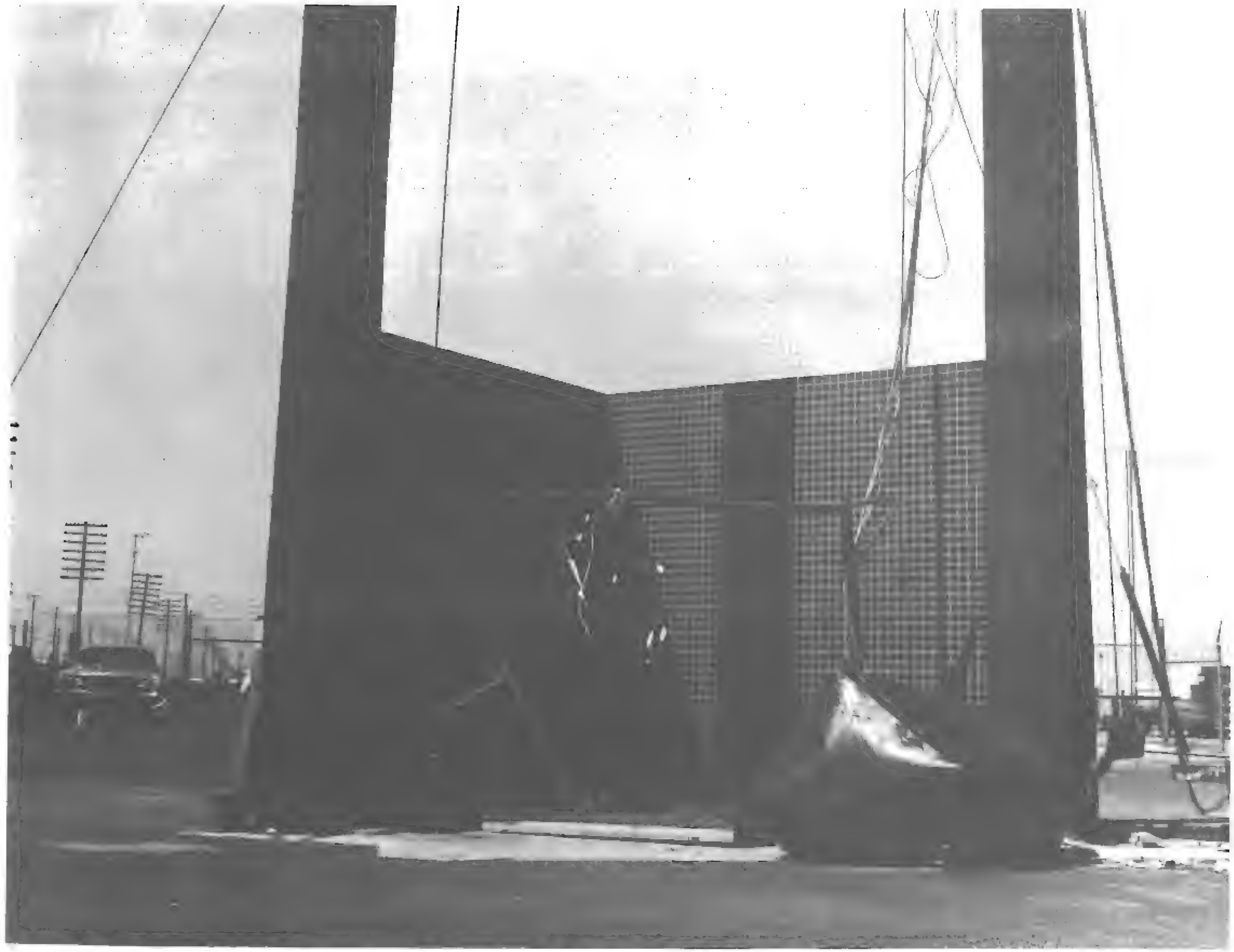


Figure 25. Tank Cut by Clip, Shown After Rebound.

Figure 26. Close-up of Cut and Leakage.

approval was received for its use for the reason that it had not been possible to attain continuous readout with either of the two previously tried gages. The slide wire extensometer also eliminated the hazard of tank damage and improved somewhat the certainty of obtaining maximum strain readings on the tank wall. An instrumented tank is shown in Figure 27.

II. PHOTOGRAPHIC RECORDING

Two Fastax cameras, operating at a nominal speed of 2000 frames per second, were focused on adjacent faces of the impacting tank.

Behind the impacting tank, and in full view of the cameras, were placed two 8-foot x 8-foot reference backgrounds which were lined with a 2-inch x 2-inch grid. The photographed faces of most tanks also had this same grid spacing. Smaller overall size reference backgrounds located beside the impacting tank were used due to the nature of the photographic requirements on some drops but were not as satisfactory from a data analysis standpoint. A 16-segment timing wheel operating at 3600 rpm was included in the view of one camera for a time reference. Each segment was equivalent to 1/960 second, or approximately 1 millisecond.

A television camera with a Sony videotape recorder was used on drops to provide an immediate preliminary examination of the tank impact. While not used for data acquisition, this did permit review of impacts for marginal areas and corrections prior to subsequent drops which would not have been possible with the Fastax due to the time delay involved in processing film.

III. VISUAL STRAIN DETERMINATION

Inasmuch as the electronic strain data was incomplete and, in some cases, indicated elongations believed to be beyond the capability of the constructions utilized, it was decided to evaluate strains indicated by the 2-inch grid network painted on the tanks. The procedure used was as follows:

Using static projection of frames of the Fastax film, 6-inch horizontal spans were selected for measurement at locations of 25, 50 and 75% of the tank height. Although the impact point remained essentially the same distance from the cameras on each drop, measurements were made of the selected spans while the tank remained in free fall to serve as a reference for 0% elongation and to take into account any camera-to-tank distance change.

Upon impact, measurements were made at these same heights on the projected tank wall at approximately 3-millisecond intervals to determine the elongation curve. Since it was recognized that the expanding tank wall would approach the camera and therefore produce

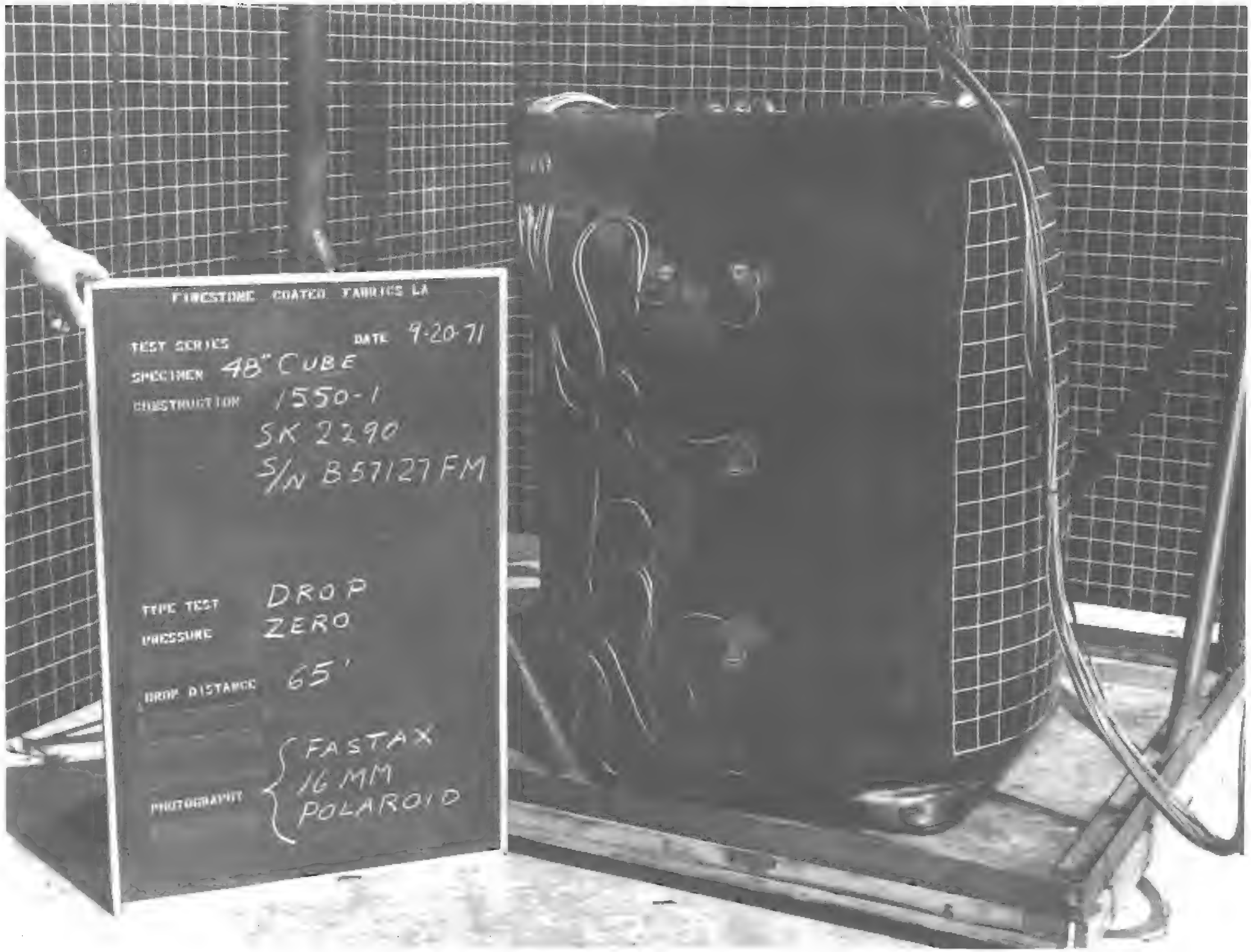


Figure 27. Slide-Wire Extensometers on Tank Prepared for Drop.

an enlarged apparent image on the film, and since measurements made from film would necessarily be those of the chord of an arc on the expanding cylindrical tank wall rather than of the arc itself, these two offsetting errors were evaluated for net effect on true elongations determined in this manner. It was found that the true elongation would be 99.6% of the apparent at 0% elongation (but with the tank in cylindrical shape) and 98.4% at 20.0% elongation. Since these are within the experimental error of measurement, no correction was considered necessary.

Elongation measurements in addition to the three mentioned above were made on three tanks. These were:

A. Configuration G/G-1 Hydraulically Coupled Tank

Measurements were made at 7, 12 and 17 inches from the impact face on the bottom tank and at the same distances from the lower surface of the upper tank.

B. Configuration L Tank

Measurements were made at approximately 6 inches above and below the side fitting horizontal centerline to determine effect of the fitting on strains in the adjacent panel.

C. Configuration K Tank

Vertical strain measurements were made at the 15-, 30- and 45-inch levels to demonstrate the vertical shrinkage of the tank wall during horizontal expansion after impact.

IV. DATA PRESENTATION

Pressure and strain data from the oscillograph record were smoothed as discussed previously and are presented in graphical form in Figures 15 through 22 as the P and E curves.

All strain data obtained by visual measurement of film records are reported in Figures 15 to 22. Pertinent data from the drop log for all tanks tested is given in Table II, although only those tanks which successfully passed the impact tests will be considered for further discussion.

DATA ANALYSIS

I. DISCUSSION OF RESULTS

Considerable unresolved discrepancy exists between the instrumented measurements of elongation and those obtained by visual measurement of grid patterns on still projection of the Fastax film.

Certain patterns of impact behavior have been developed, however. The first of these is the generalized relationship of pressure with time. It will be noted from the pressure traces that a number of them possess the general pattern shown in Figure 28.

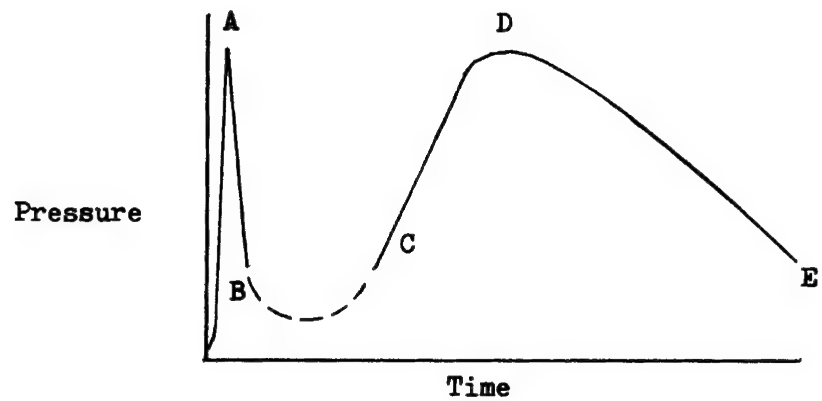


Figure 28. Typical Pressure Variation with Time.

The initial spike, A, usually occurred between 0.7 and 1.5 milliseconds of the nominal impact. The term nominal is used advisedly since it is almost impossible to determine the precise instant of impact due to the slight cant at which most drop platforms meet the tower base. Visual examination of Fastax film often shows one corner or side touching the base while the rest remains very slightly elevated. Instrumentation consequently may begin to show a slight pressure increase of relatively long duration (1-2 ms) before the spike occurs. The upper part of the trace was usually poorly defined due to the extremely fast movement of the light-beam oscillograph. It occurred predominantly on the lower two pressure transducers (P1, P2) but was not limited to these, and it occurred nearly simultaneously on all transducers where it appeared. The most satisfactory explanation to be suggested is that it is a sonic wave whose intensity depends largely on the "flatness" of the impact. Since the velocity of sound in water is approximately 4700 feet per second, the elapsed time between the P1 trace (3 inches from impact face) and P4 (36 inches from impact face) would be only 0.6 millisecond on a 48-inch tank. Due to the short duration, the impulse to the tank

wall is so small that no visual effect is produced regardless of the pressure. On the figures where the impulse is included, the intent primarily is to show its presence rather than to indicate precisely the pressure reached.

The delay period, B to C, is primarily a function of the distance of the measuring point at which the rising tank pressure equals the declining sonic pulse, if one exists at the level of measurement. The time of the crest of the pressure peak, D, depends again upon distance from the impact face; and, although evident in the pressure curves for Configuration H, Figure 18, and Configuration I, Figure 19, it is consistently more evident in the horizontal strain curves determined visually for all tanks. The visual evidence of this pressure crest took the form of an ascending wave front which began at the impact face and proceeded upward with a relatively uniform velocity to the top of the tank. An attempt was made to determine the average wave velocity relative to the tank wall between 20% and 80% of the height by observation of still projections of the Fastax film. The results of this are given in Table II.

TABLE II. ASCENDING PRESSURE WAVE VELOCITY

	Wave Velocity (ft/sec)
48-inch tanks:	
Configuration H	203
Configuration I	196
Configuration J	181
Configuration G/G-1	189
60-inch tanks:	
Configuration K	178
Configuration L	177

The decline from the pressure crest is normally much slower than the rise, as is indicated by both pressure and elongation curves, and occurs as a subsidence of pressure throughout the tank.

Although not conclusively proven in this series of tests, another factor appears to affect the maximum pressure reached. It can be noted that both tanks of Configuration E gave lower pressures than those of equivalent size tanks (Configurations H and I) of the reinforced, heavier construction. It thus appears that a stronger or higher modulus construction tends to increase pressures at the same time that it protects against them, although not necessarily in the same ratio.

Visual strain curves were made for all tanks of 1550-1E construction in the horizontal direction. However, vertical strains were determined on the Configuration K tanks at levels corresponding to those used for horizontal measurements. A series of vertical contractions somewhat less in magnitude than the corresponding horizontal elongations is evident. The cyclic oscillations are evident here also. Inasmuch as the area of primary interest was that of horizontal strains, other tanks were not evaluated for vertical strains except for the Configuration I tank at the fitting elevation on an adjacent panel. It follows the same general pattern as the Configuration K tank.

The horizontal strain curves, H2 to H4, indicate the passage of the ascending pressure wave and a general diminishing of maximum pressure with distance from impact face. On the Configuration L tank, the strain at the fitting centerline, as measured in the adjacent panel, appears to reach a maximum somewhat out of phase with the H3H and H3L curves. This may be due solely to measurement error, but the fitting behavior during the pressure wave passage indicates that it is not. Instead of moving smoothly from the relatively unstrained position ahead of the wave to the stressed position behind it, the fitting underwent two rapid oscillations about its horizontal centerline. This would tend to account for the cyclic strain pattern in curves H3L and H3. It seemed to have little effect on curve H3H, however. It is believed that the mechanism which produces the fitting oscillation is as follows:

The ascending pressure wave, moving along the tank wall before encountering a fitting, elongates the tank approximately 20% horizontally and causes it to contract approximately 15-17% in the vertical direction.

When the wave encounters a fitting, both horizontal elongation and vertical contraction are impeded. The fitting ring and cover plate effectively do not undergo deformation. The combination of panel plies and fitting flanges surrounding the ring, while flexible, is more restrictive than the tank wall. In consequence, the panel areas horizontally adjacent to the fitting are restricted from vertical contraction and cannot elongate to the same degree as panel areas above and below the fitting. The result is a high-tension area on each side of the fitting in which the tension diminished from the fitting horizontal centerline both upward and downward to the fitting flange areas above and below the fitting. The differential vertical contractions

between the panel areas horizontally adjacent to the fitting and those immediately above and below the fitting produce an excess or relative "looseness" of the cell wall/flange combination in these areas to the extent that horizontal wrinkles are produced. These wrinkles then permit the fitting to oscillate as the pressure wave passes. The presence of the wrinkles is shown in Figure 29.

This behavior therefore indicates the following effects produced by fittings on vertical wall of cells:

1. High tensile forces are concentrated in the panel and flange areas adjacent to the fitting ring horizontally.

2. The restriction caused by the fitting effectively increases the modulus at the fitting elevation and consequently the pressure at that elevation, although the instrumentation was not sufficiently sophisticated to indicate this.

3. Multiple fittings, particularly at the same elevation, should exaggerate the increase in tension.

II. CONCLUSIONS

A. Pressures developed in impacting cubes are in the range of 130-150 psi for normal MIL-T-27422B Phase I constructions and 170-200 psi for reinforced constructions adequate for larger tanks.

B. Insufficient evidence was developed in this program to conclude that pressures developed in 60-inch tanks are significantly higher than those in 48-inch tanks of the same base dimensions.

C. Hydraulically coupled tanks undergo much the same sidewall strains as unit tanks of the same base dimensions and capacity. They are subject, however, to additional stresses of considerable magnitude at the coupling fittings both during impact and during the subsequent rebound. (See Figure 30 for rebound sequence.)

D. Fittings in vertical walls produce localized areas of high tensile stress horizontally adjacent to the fittings.

E. The only "hydraulic ram" of consequence is the ascending pressure wave.

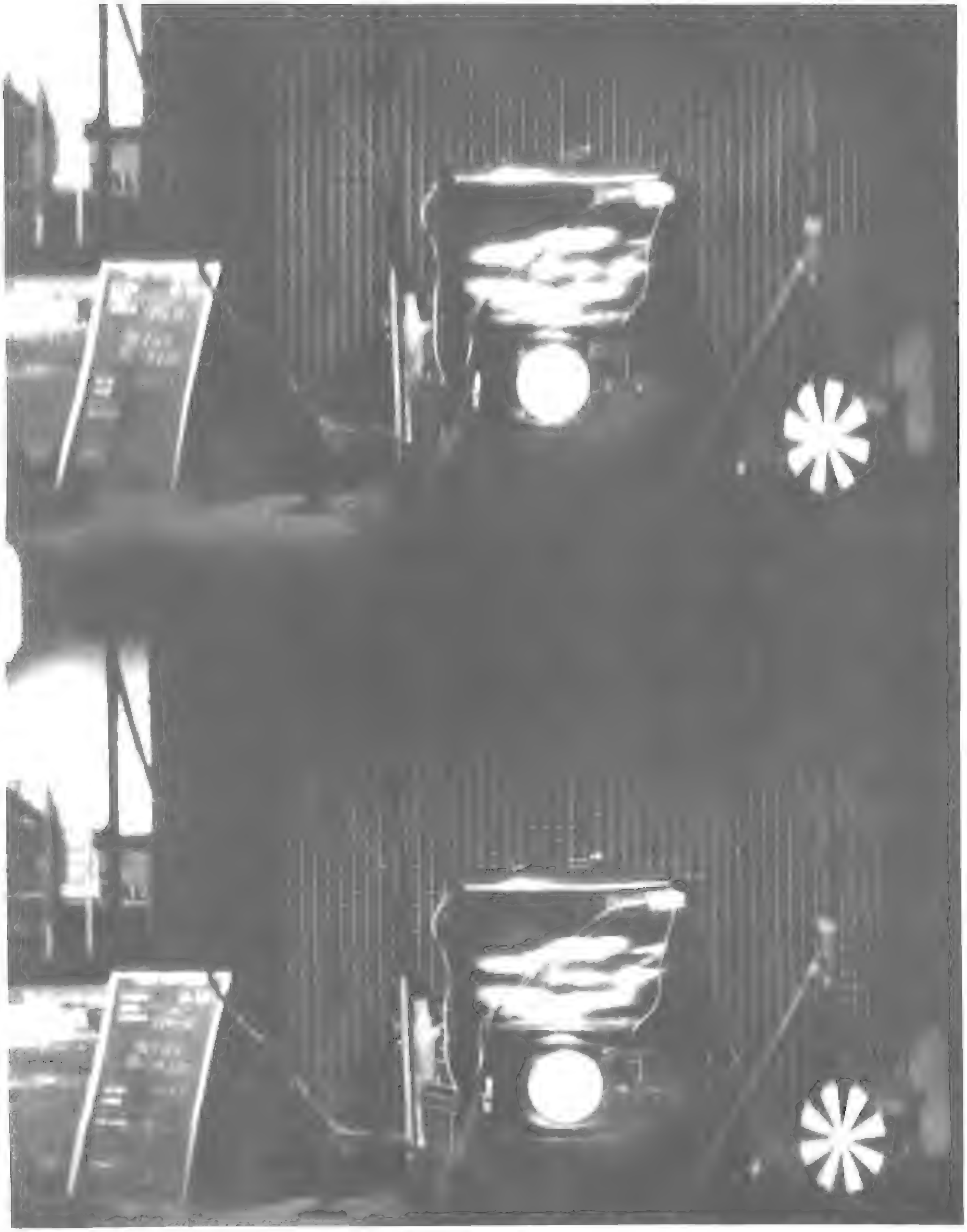


Figure 29. Strain Pattern Adjacent to Fitting.

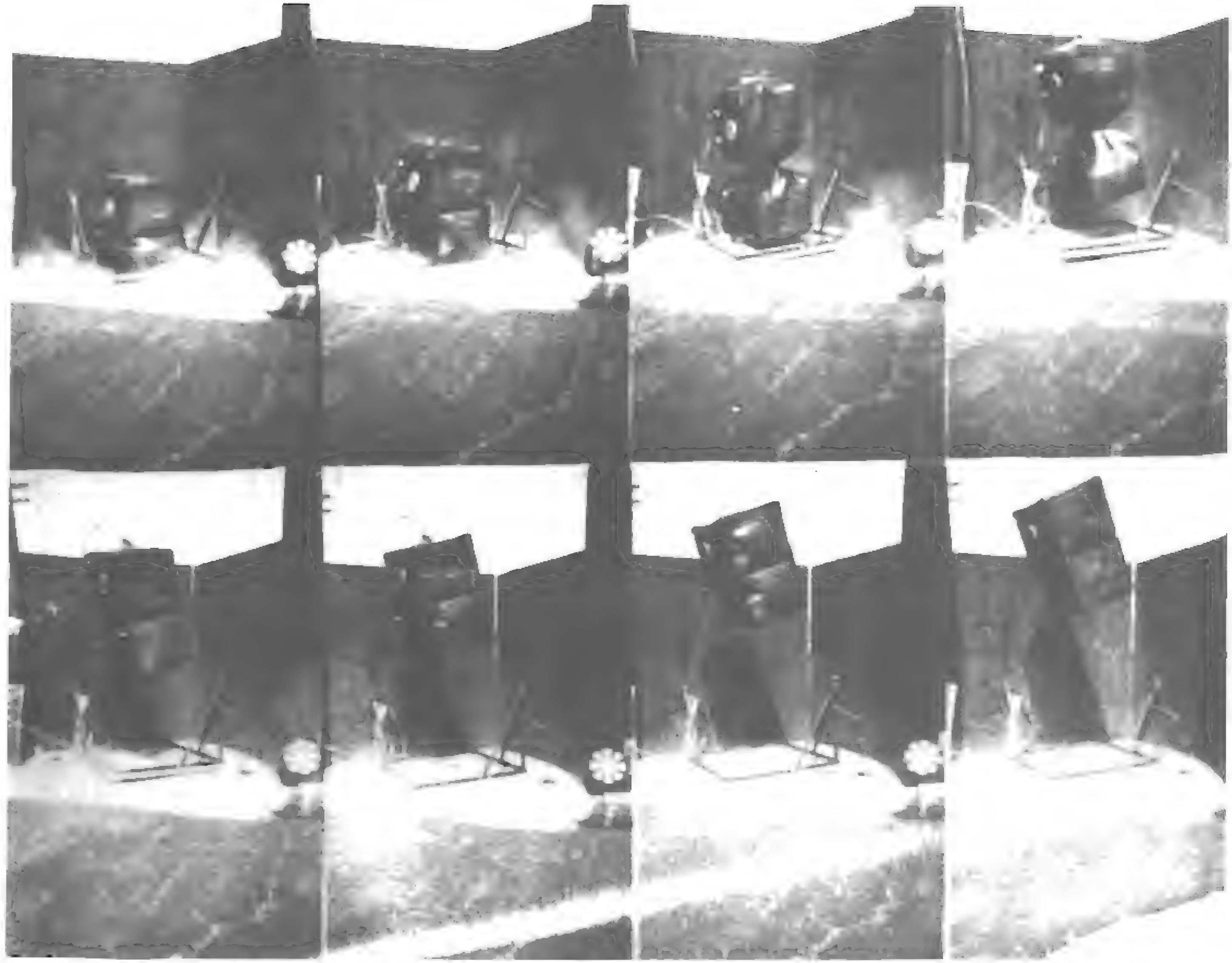


Figure 30. Rebound Sequence of Hydraulically Coupled Tank.

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UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Firestone Coated Fabrics Company
Division of Firestone Tire and Rubber Company
Magnolia, Arkansas

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
EVALUATION OF VARIOUS SIZES AND CONFIGURATIONS OF FUEL TANKS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report

5. AUTHOR(S) (First name, middle initial, last name)
D. L. Byerley

6. REPORT DATE
December 1973

7a. TOTAL NO. OF PAGES
48

7b. NO. OF REFS

8a. CONTRACT OR GRANT NO.
DAAJ02-71-C-0031

b. PROJECT NO.
Task 1F162203A529

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
USAAMRDL Technical Report 73-74

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
FCFC Report 2097

10. DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Eustis Directorate
US Army Air Mobility R&D Laboratory
Fort Eustis, Virginia

13. ABSTRACT

Eighteen tanks with a 30-inch x 30-inch base dimension and heights of 48 and 60 inches of qualified crashworthy constructions were impacted from 65 feet. Nine of these failed adjacent to fittings on side panels. All tanks without side fittings passed the impact test regardless of constructions used and with average densities varying from 1.11 to 1.75. Indicated pressures were in the 130-150 psi range for two tanks of Firestone 1550-1 construction and 170-200 psi for a reinforced, heavier revision of this construction.

Strains determined by visual measurement of film records varied from 10 to 21 percent depending on the location on the tank. Those indicated electronically were as high as 60% in the case of the Configuration L tank. The discrepancy between the two methods of strain measurement has not been resolved.

The presence of fittings unquestionably increases the stress in the tank wall in the immediate area adjacent to these fittings and reaches a maximum as the expansion wave of the impacting tank passes the horizontal centerline of the fitting.

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	ROLE	WT	ROLE	WT	ROLE	WT
Fuel Tanks						
Crashworthy						

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